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Report No. 2

Second Quarterly Progress Report

1 October to 31 December 1962

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RESEARCH ON DIELECTRICS FOR MICROWAVE ELECTRON DEVICES

Prepared for:

U.S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

TASK NO. OST 76-10-318-28

Ac-3

CONTRACT NO. DA-36-039 SC-90856

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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10 By: L. Feinstein, J. Bordeaux, and D. Peters, 12 48p.

16 SRI Proj. PMU-4160

Object of the Research: To investigate and identify the factors that contribute to the behavior and failure of dielectric materials used in microwave electron devices.

1 ARPA This research is a part of Project DEFENDER, sponsored by the Advanced Research Projects Agency, Department of Defense, under Order 318-62 and Project Code No. 7300, and is conducted under the technical guidance of the U.S. Army Electronics Research and Development Laboratory.

Approved:

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A. E. GORUM, DIRECTOR
MATERIAL SCIENCES DIVISION

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PURPOSE

The purpose of this research is to study the properties of dielectrics used in microwave devices, with special emphasis on materials used for microwave windows. It is concerned with study and understanding of the factors that influence the properties of the dielectric material. The first material to be studied is aluminum oxide. This material will be investigated to determine the relationship between its properties and its structure as influenced by impurities, defects, additional phases, and particle bombardment. Among the important problems to be considered is the mechanism of breakdown of the dielectric as a function of these parameters.

The approach undertaken in this program is that of preparation of high purity films of the dielectric having known compositions and structures. It is anticipated that this attack on the problem, when correlated with the analytical study of the material, will allow identification of the contribution of the various factors to the behavior of the materials studies.

ABSTRACT

The theoretical study of dielectric breakdown ~~has been~~ ^{was} continued. A number of different possible mechanisms have been described and their distinguishing features identified. ^{not} These features led to the design ^{step} of experiments that should indicate the breakdown mechanisms in effect ^{that} for each particular experiment.

Visits were made to a number of people concerned with dielectrics and microwave devices. The purpose of these visits was to exchange information and ideas about the general problem area of dielectrics.

Measurements of the properties of sapphire ^{were} have been begun. The first set of tests are concerned with resistivity as a function of temperature and as influenced by a boundary, and with determination of vacancy concentration by spin resonance.

Work on the ultrahigh vacuum system is progressing, and it should ~~be completed by the end of the next quarter.~~

Preliminary experiments on growth of aluminum oxide films are ~~in progress.~~

A cavity for testing the effect of ionization of gas in voids of window materials ~~has been~~ designed. Attempts are being made to arrange for use of a facility in which to conduct the tests.

CONFERENCES

October 4, 1962. Mr. L. Heynick of USAELRDL visited Stanford Research Institute to discuss the progress of the project.

November 29, 1962. Lt. Col. W. B. Lindsay of ARPA and Mr. L. Heynick of USAELRDL visited Stanford Research Institute to discuss the progress of the project.

The following people and institutions were visited by L. Feinstein for discussion of problems in dielectrics. The report includes a section describing these visits.

November 13, 1962	Prof. A. von Hippel	MIT
November 14, 1962	Drs. R. Buttman, G. Guernsey	Lincoln Laboratories
November 15, 1962	Dr. J. Pentacost	Melpar
November 16, 1962	Mr. D. Churchill	Sperry Gyroscope Co.
November 19, 1962	Messrs. Heynick and Del Vecchio	USAELRDL
November 20, 1962	Prof. P. Warters	Princeton Univesity
November 20, 1962	Dr. A. Rose	RCA Laboratories
December 4, 1962	Prof. P. Gibbs	University of Utah
December 17, 1962	Prof. G. Wannier	Oregon University

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FACTUAL DATA

I Definition of the Approach

In the discussion of the purpose of this research, it was pointed out that the effort would be directed toward study and understanding of the basic properties of the dielectric material. It was further pointed out that the approach to be taken was based on preparation of high purity films of the dielectric. It is imperative that an attempt be made to produce a film of the highest possible purity and that all efforts be made to identify and measure quantitatively those impurities which do become a part of the film.

The approach which, in our judgment, presents the best possible opportunity to prepare very high purity films of a dielectric material is by deposition in an ultra-high vacuum system. Ultra-high vacuum systems which are capable of operating at pressures lower than 1×10^{-10} torr have been designed and constructed by another group of workers at Stanford Research Institute,¹ and are the models for the equipment to be used for this investigation.

A. The Vacuum Technique

The system consists of two vacuum chambers, one inside the other. The outer chamber is a large high vacuum system, generally consistent with standard high vacuum system designs. The inner system is especially designed and has several distinctive features, as follows: (1) it is bakeable to at least 800°C ; (2) it has methods of mechanical manipulation within the inner ultra-high vacuum chamber; (3) it is being provided

with ports which allow the passage of chemicals from the high vacuum chamber to the ultra-high vacuum chamber; (4) it is being provided with a quadrupole mass spectrometer for the purpose of attempting to monitor the impurities in the system before, during, and after deposition of the film. Furthermore, the composition of the films will be investigated with this device by monitoring the materials given off during intentional destruction of some of the films.

B. Deposition of the Film

It is generally conceded that there are three major categories into which thin film growth can be divided: thermal evaporation, sputtering, and reactive deposition. Thermal evaporation and sputtering techniques are similar in nature in that both utilize as a source that material which is also the resultant film. A thorough discussion of the relative merits of thermal evaporation and reactive deposition has been given by Shoulders.¹ It is believed on the basis of those arguments that, for the purposes of this research, the technique of reactive deposition of a film would produce the best results, from both experimental and purity-of-product considerations.

The technique of reactive deposition involves bringing together at the substrate surface two or more reactive species under the conditions necessary to cause the desired reaction to take place, resulting in deposition of the film on the substrate surface. A more detailed discussion of specific chemical considerations is given in a later section of this report.

C. General Discussion of Approach

The essence of this entire research is the belief that the foregoing experimental approach offers the best possible method of achieving a material which will allow study and understanding of the basic properties of the dielectric material.

It should be recognized that any experimental attempt to upgrade the purity of already high purity materials is faced with some difficulties, and the method of approach chosen is not without experimental problems; however, it is believed that this approach offers the minimum of difficulties and the greatest opportunity for overcoming most of the problem. The problems specific to the experimental techniques involved in this approach will be discussed in later sections of this report.

Critical examination of these materials, once prepared, is of utmost importance. For this reason, investigation of a number of techniques is being undertaken and is discussed in the body of the report.

II Further Consideration of Dielectric Breakdown

In the preceding report the concepts of thermal and intrinsic breakdown of dielectrics were introduced. Thermal breakdown is essentially dependent on the lattice temperature and the applied field and there is a critical lattice temperature T_0' which determines the breakdown field. Intrinsic breakdown is essentially dependent upon the applied field, which affects the kinetic energy of the electrons. It was shown that when electron energy gained from the applied field exceeds that lost to the lattice by electron-phonon interaction breakdown can occur. Intrinsic breakdown is classified by Stratton² into three categories: (1) collective, (2) avalanche, (3) internal field emission. A discussion of these three phenomena follows.

A. Collective Breakdown

Collective breakdown is a condition that may be described as absorption by a sufficient number of free electrons in the dielectric of enough energy from the applied field to produce excessive current in the dielectric. The current may be localized in a narrow path through the material or it may be evenly distributed through it depending on the field configuration. Because of the excessive current, the lattice temperature increases to the critical temperature, leading to puncture or fracture of the dielectric and/or chemical changes in the material itself. This is distinct in two respects from thermal breakdown, which is determined by lattice temperature. In thermal breakdown the thermal conductivity of the lattice is so low that energy transfer from electrons to lattice causes a temperature increase which increases electrical conductivity and hence further increase of lattice temperature to the critical value. The thermal breakdown field is therefore determined by the temperature dependence of the electrical conductivity. The second distinction is that thermal breakdown is accompanied by a relatively long formative time necessary to raise the lattice temperature to the critical value. In collective breakdown the temperature rise of the lattice is of a shorter, transient nature due to the surge of current at the breakdown condition.

The basis of the collective breakdown concept is that free electrons absorbing energy from the applied field are subject to collisions with other electrons and the lattice (phonons). Breakdown can occur if the rate of energy exchange between electrons exceeds the rate of energy loss to the lattice. There are two cases to be considered:

the first is the ideal case, the perfect crystal; and the second is the crystal with imperfections (impurities and defects).

In the perfect crystal the only mechanism of energy exchange between free electrons and lattice is electron-phonon collisions. It is assumed therefore that there must be an initial minimum electron density of sufficient magnitude so that interelectronic collisions determine the energy distribution of the electrons. The distribution function describing electron energy in this case is Maxwellian, with mean electron temperature T_e , corresponding to the electron energy, which is a function of the applied field. The electron temperature is not necessarily the same as that of the lattice. It is determined by the balance of the rate of energy absorbed by the electrons and exchanged due to interelectronic collisions and that transferred to the lattice by electron-phonon collisions. The energy exchange due to electron-phonon collisions is small compared with that of the interelectronic collisions. Therefore, with a sufficiently high field the average electron temperature can exceed that of the lattice and increase without limit. When this condition exists breakdown occurs.

For a particular material the energy exchange, and hence the electron temperature, depends on the applied field. If the field is less than E_c , the critical field, the system is stable. If the field exceeds E_c the system is unstable, the average energy gained by the electron system exceeds that transferred to the lattice, electron temperature increases rapidly, and breakdown occurs. E_c can be called the collective breakdown field. It is of the order of von Hippel's breakdown field F_H .

The value of the breakdown field E_c is determined by the properties of the material. It can be specified, according to Stratton, for the case of covalent crystals with acoustic vibrations active as:

$$E_c = \frac{\hbar N^{1/3}}{m\mu_\alpha(\Theta)} \chi_2 \left(\frac{T_0}{\Theta} \right) \quad (1)$$

$\chi_2 \left(\frac{T_0}{\Theta} \right)$ is a function dependent upon the lattice temperature and its relation to the Debye temperature for the material.

$$\chi_2 \left(\frac{T_0}{\Theta} \right) = \begin{cases} \begin{pmatrix} 0.30 \\ 0.25 \end{pmatrix} \left(\frac{T_0}{\Theta} \right)^{1/2} & \text{if } T_0 \gg \Theta, \begin{cases} kT_c = 0.56 W_0 \\ kT_c = 0.45 W_0 \end{cases} \begin{cases} n > n_c^* \\ n^* > n > n_c \end{cases} \\ \begin{pmatrix} 0.14 \\ 0.059 \end{pmatrix} & \text{if } T_0 \ll \Theta, \begin{cases} kT_c = 0.60 W_0 \\ kT_c = 0.52 W_0 \end{cases} \begin{cases} n > n_c^* \\ n^* > n > n_c \end{cases} \end{cases} \quad (1a)$$

N = number of unit cells per unit volume

$\hbar = h/2\pi$

m = effective mass of electron $\sim \frac{2m_0 a^2 E}{h^2}$ (Brillouin approximation)³

$\mu_\alpha(\Theta)$ = weak field mobility

Θ = Debye temperature for dielectric crystal

k = Boltzmann's constant

T_0 = lattice temperature

T_c = Critical electron temperature corresponding to E_c

$W_0 = (k\Theta)^2/8 \text{ ms}^2$ (energy associated with lattice vibrations)

s = velocity of sound in material

n = free electron density

n_c = free electron density necessary for breakdown

n_c^* = free electron density necessary to ensure that momentum exchange is principally among electrons

m_0 = mass of free electron

a = lattice content of crystal

E_g = energy gap of material

h = Planck's constant.

The free electron density necessary for breakdown, n_c , is given by

$$n_c = 10^{13} \left(\frac{T_0}{293} \right)^{1/2} \left(\frac{W}{kT_0} \right)^2 \left(\frac{\epsilon}{10} \right)^2 \left(\frac{s}{10^5} \right)^2 \left(\frac{10^3}{\mu_Q} \right) \left(\frac{m}{m_0} \right)^{1/2} \text{ cm}^{-3} \quad (2)$$

W = average energy of electron system

ϵ = relative dielectric constant

μ_Q = mobility of electrons at field approaching E_c .

This value for n_c ensures that the energy distribution of the electrons is Maxwellian. There is in addition the requirement that interelectronic collisions dominate the rate of change of momentum for electrons. To satisfy this second requirement the electron density must exceed n_c^* defined by

$$n_c^* \simeq (kT_0/ms^2) n_c \quad (3)$$

where the term ms^2 represents the energy lost to the lattice per collision and kT_0 represents the thermal energy of the electron.

For aluminum oxide, using an energy gap of 7.3 ev and a lattice constant of 4.75×10^{-8} cm, the ratio of effective electron mass to free electron mass is 1.1 by the Brillouin approximation. With the value of m/m_0 and assuming a mobility of about $10 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$, a dielectric constant of 9, and a velocity of sound $11 \times 10^5 \text{ cm sec}^{-1}$ for aluminum

oxide, the expression for n_c becomes

$$n_c \approx 1 \times 10^{17} \left(\frac{T_0}{293} \right)^{1/2} \left(\frac{W}{kT_0} \right)^2 \text{ electrons cm}^{-3}$$

If the lattice is at 300°K and the average electron energy is 1 ev, the electron density n_c for breakdown is about 6×10^{17} electrons cm^{-3} and n_c^* becomes approximately 2×10^{19} electrons cm^{-3} . Assuming a value for mobility of the electrons in the material, it is possible to determine the order of current associated with the breakdown field for a pure material. It should be noted that the value of 1 ev is the order of electron temperature or energy that Fröhlich and Paranjape consider necessary for breakdown in nonpolar crystals.

The breakdown field can be evaluated by use of equation (2). The volume of a unit cell of aluminum oxide is 260 \AA^3 , and, assuming a weak field mobility of $5 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ and a Debye temperature of 1000°C , E_c is $4.4 \times 10^5 \text{ V cm}^{-1}$ if the electron density is greater than 2×10^{19} electrons cm^{-3} , and E_c is $1.8 \times 10^5 \text{ V cm}^{-1}$ if the electron density is less than 2×10^{19} electrons cm^{-3} but greater than 6×10^{17} electrons cm^{-3} . Using the above values of E_c , N , and μ_α , the current density at breakdown in a pure crystal could be in the order of 10^8 amperes cm^2 .

The preceding discussion has been concerned with pure crystals, where phonon-electron interaction is the mechanism of energy loss of the free electrons. It indicates the dependence, for a pure crystal, of the critical field and free electron density on the parameters of the material. However, pure crystals are not available; there are always some imperfections in the material.

The theory of collective breakdown for pure crystals is based on the concept of direct energy transfer from free electrons to the lattice. In a perfect crystal free of imperfections there are no electrons trapped at excited levels. However, in a real crystal imperfections do exist and there are electrons trapped at excited levels within the forbidden band of the material. In this case the energy transfer process can take place from the field to the free electrons, then to the trapped electrons, and then to the lattice. If the density of imperfections is very great, this process can predominate over the direct energy exchange between free electrons and phonons. Fröhlich⁴ and O'Dwyer⁵ have developed an expression for the breakdown field for the case of the crystal with many imperfections. Their argument is premised on the concept that there is a greater density of electrons in the trapped states than in the conduction band. This argument, when combined with the balance of energy transfer, leads to an expression for the breakdown field in the form:

$$E_c \cong K \exp (\Delta V/kT_0)$$

where K = constant determined by Debye temperature, relaxation time, effective mass of electron, and number of unit cells per unit volume

ΔV = energy separation between bottom of conduction band and excited impurity levels.

Thus for the crystal with a large density of imperfections, the breakdown field rises with deeper trapping and decreases with increased temperature.

B. Avalanche Breakdown

Avalanche breakdown is described as the process whereby electrons gain sufficient energy from the field to form ionizing collisions with

lattice atoms, thereby liberating more electrons and leading to the avalanche. The breakdown field E_b is determined by equating the energy supplied by the field to the electrons with the energy necessary to raise the lattice temperature to T'_0 , the critical temperature. This is analogous to thermal breakdown with an extremely short time lag.

A single free electron under the influence of a sufficiently high field can ionize a lattice atom, producing two free electrons. This process can be repeated until the electrons leave the dielectric. If the original electron is capable of i ionizing collisions while it is in the dielectric, 2^i free electrons will be formed. The free electrons will travel in a narrow track in the direction of the field. The cross section of the track will be controlled by diffusion. Seitz⁶ has estimated that, for a 1-cm-thick sample, i need be approximately 40 for the lattice temperature to rise to T'_0 , the breakdown temperature.

In determining E_b , provision must be made for energy loss due to interelectronic collisions, and for recombination. An expression for E_b which also takes into account scattering by acoustic vibration is

$$E_b = \frac{I}{el_a} / \left\{ \log_e \left[\frac{L}{il_a} \left(\frac{kT_0}{ms^2} \right)^{\frac{1}{2}} \right] + 1/2 \left(\frac{kT_0}{ms^2} \right)^{\frac{1}{2}} \right\}$$

where I = ionization energy for dielectric

l_a = mean free path of electron

L = thickness of dielectric

The inverse dependence of E_b on L is significant in that this dependence does not occur in collective breakdown.

C. Internal Field Emission

Internal field emission may be described as the tunnelling of electrons through a barrier under the influence of a high field. In a dielectric the tunnelling process can occur from the valence band to the conduction band across the energy gap. It can also occur from an impurity level to the conduction band. Chynowith⁷ considers the field emission process as a source of free electrons which may then lead to breakdown by the other processes described. The current density due to field emission is

$$J = (ze^2/a^2h) V \exp \left(- \frac{\pi^2}{2eh} \frac{2m}{E} \frac{E_g^{3/2}}{E} \right)$$

where z = the number of electrons per unit cell

a = unit cell dimensions

E_g = energy gap or energy difference between the impurity level and bottom of conduction band

E = applied field

V = voltage drop in a distance x .

The above expression is derived from Zener's theory of breakdown. However, no account is taken of recombination processes that can occur, so the currents predicted will be somewhat higher than those developed by field emission.

There are significant differences between the breakdown processes described. Collective breakdown is independent of specimen size and for imperfect materials is dependent on temperature; the breakdown field decreases as lattice temperature increases. Avalanche breakdown shows a dependence on specimen thickness, a weaker dependence on lattice temperature, and a time lag for the avalanche currents to build up. In addition,

the pre-breakdown current should be noisy while they are building up. These differences may be observable in well-controlled tests, and so the breakdown mechanisms may be indentifiable.

D. Space Charge Effects

Rose⁸ and Lampert⁹ have studied extensively the problems of space charge effects in solids, and their concepts should be applicable to the study of breakdown in dielectrics. When an insulator is located between electrodes to which a potential is applied, there can be two sources of current at moderate fields. These sources are thermal generation of carriers within the insulator and injection of carriers into the conduction and valence bands if the contacts are ohmic. The thermally generated currents follow an Ohm's law dependence on the applied voltage. With carrier injection, a space charge somewhat analogous to that of a vacuum diode is built up in the dielectric. For a material without traps the current within the insulator varies as the square of the applied voltage. When shallow traps are present in the insulator, the square law dependence of current persists. However, when there are deep traps present within the material, the current becomes an exponential function of the voltage as the traps are filled.

The implications of this approach are that the space charge limited currents within an insulator are strongly affected by the trap distribution and density. If trap density is less than density of carriers, the currents build up as functions of the voltage as described above and breakdown can occur. If trap density is greater than the density of carriers, the buildup of space charge limited currents is suppressed.

The concept of carrier injection and associated space charge indicates a possible mechanism contributing to breakdown. Breakdown can occur by virtue of an excess of carriers over the available traps under the influence of a high field, or it can occur as an avalanche or collective breakdown with free electrons available from the injection process.

E. General Comments on Breakdown

It is important to note that generation of carriers can also be accomplished by penetrating radiation. Pensak¹⁰ has demonstrated induced conductivity in silica. The mechanism is primarily one in which the penetrating high energy particles liberate bound electrons by the collision process. The low energy free electrons can be trapped, and build up a space charge. However, if trap density is low and/or the applied field across the dielectric is high, the free electrons can absorb enough energy to induce breakdown.

There are a number of directions of investigation implied by the preceding discussion of breakdown phenomena. Probably the most immediate is the need to isolate the different processes described as the breakdown mechanisms in dielectrics. Both Stratton and O'Dwyer have reported on the work of investigators who have conducted experiments aimed at this goal. Most of the reported work has been on alkali halides and the attempts at correlating breakdown fields with theory have been, at best, marginally successful.

There are a number of apparent reasons for the lack of consistency of data and for poor correlation with metallic contacts on the dielectrics,

and carrier injection and space charge effects could have influenced the breakdown processes. It would then be difficult to isolate one process from the other. The purity of the specimens and location of traps within the specimens were not well defined. The influence of these two factors has been discussed and their importance in breakdown phenomena is obvious. The distribution and identification of defects in the specimens were not known and their importance to the breakdown processes in terms of traps or scattering effects is significant.

It is not possible to identify the impurity and defects content of specimens completely. However, there are available sufficient tools to gain a rather complete knowledge of their distribution in the material to be studied. To name a few: spin resonance techniques can be used to identify paramagnetic impurities and also, with either electron or light injection, to identify vacancies in the material; etching can be used to identify surface dislocations; electron beam microprobe techniques can be used to identify impurities; and electron injection can be used to identify the density and distribution of traps. In addition, experiments on the material can be conducted in a manner to avoid carrier injection during the breakdown studies. This can be accomplished by using blocking contacts to apply the field to the specimens.

It is interesting to speculate about the implications of the different breakdown theories for dielectrics used in microwave devices. Perhaps the most significant implication is that resulting from considering the effects of electron and X-ray bombardment of window dielectrics. Both of these forms of penetrating radiation can lead to space charge currents and/or excess free carriers in the windows. This is because the

electrons in the microwave tube are subject to high fields and some of them will be deflected to the window in the wave guide. When the electrons are in the guide they can generate X-rays by collision with the guide walls or they can hit the window directly. In either case there is a strong probability that the window will be subject to particle radiation.

There is also the high probability that the window will be subject to transverse fields as well as a parallel r.f. field. The transverse field can be a d.c. field caused by ionization of residual gas within the tube or by multipactor at the window. This combination of applied field and particle bombardment can lead to breakdown conditions.

There are a number of experiments that can be conducted to study the breakdown processes and also to provide the background information necessary to an understanding of them. Perhaps the most important are measurement of traps in a dielectric and the characteristics such as mobility, lifetime, effective mass of the carriers in the dielectric, and the capture cross section for carriers in the material. When these data are accumulated, breakdown measurements will have more significance in terms of relating observation to the type of breakdown process occurring in the material.

The first experiments, therefore, are those aimed at accumulating the above specified characteristics. These experiments will consist of (1) measurements of the transient and steady state space charge currents in single crystal sapphire, and (2) measurement of the Hall mobility of the carriers in single crystal sapphire.

Experiments (1) will be conducted on thin disks of sapphire that will be illuminated by either a light source or an electron source (either pulsed or steady state). The illuminated side or surface will have an ohmic (injecting) contact. In the pulsed case the transient current should indicate the transit and decay times. From these the mobility, lifetime, and capture cross section can be computed. Steady state measurements should result in data indicating trap distribution. The second experiment, Hall effect, will be conducted on small rectangular specimens of sapphire. The limitations on size are dictated by the high resistivity of the material, which necessitates relatively thin sections to attain measurable currents.

Because of the large energy gap of aluminum oxide (about 7.3 ev), the light source for excitation of carriers must be in the vacuum ultraviolet range (about 1600 Å max). This indicates the use of either a Krypton or a Xenon lamp with a lithium fluoride window. The lamp will be mounted in a vacuum system with the aluminum oxide specimen so that absorption of the photons at the required energy will be minimized. A vacuum of about 10^{-5} Torr should be sufficient.

The design of this experiment is dictated to a great extent by the types of lamps available. Suppliers of lamps are being contacted for information about the characteristics of their products and the pulser units and power supplies necessary to operate them. It should be noted that examination of the literature has not disclosed previous experiments with pulse excitation of materials with this large band gap. As soon as the lamp with the necessary characteristics is selected the construction of the experiment facility will be started.

III Visits to Workers in the Field of Dielectrics

During the second quarter a number of workers in the field of dielectrics were visited. The individuals and their comments are listed below as interpreted by Lester Feinstein.

A. Professor A. von Hippel - Massachusetts Institute of Technology

Dr. von Hippel believes that the major factor leading to failure of windows is particle bombardment, i.e., electrons, X-rays. He feels that the deleterious effect of bombardment is so great that the dielectric fails via mechanisms induced by the bombardment. His comments indicated that a potentially useful approach to window improvement would be to protect the window from particle bombardment by the use of a device that would prevent high energy particles from reaching the window.

The discussion about the properties of aluminum oxide indicated that Professor von Hippel was not very optimistic about the chances that a study of this material will indicate directions towards improving its properties. He believes that the breakdown and the dielectric properties of aluminum oxide cannot be improved appreciably. He suggests that the presently available commercial high purity aluminum oxide bodies are satisfactory and that little improvement in properties can be expected to result from further investigations and studies.

Professors Chernow and Goldner of the electrical engineering department of M.I.T. are engaged in a thin film program. They are setting up an ultrahigh vacuum facility to grow various materials by the vapor phase reaction method and are incorporating a quadrupole mass spectrometer to monitor reactants and reaction products. Their equipment and approach to

growing ultrapure materials is essentially the same as that under construction at Stanford Research Institute. However, they are working with relatively low energy gap materials and do not intend to work on aluminum oxide. In addition, they are incorporating a diffraction apparatus to study the structure of the film as it is grown. They have a problem in depositing a suitable bakeable phosphor on the high vacuum side for observation of the diffraction patterns.

B. Dr. R. Buttman, Dr. G. Guernsey, Dr. W. Muehe - Lincoln Laboratories

This group is engaged in studies of high power klystrons and is aware of the problems concerning windows. Dr. Muehe has been concerned with breakdown problems in gases, and was engaged in a discussion about the study of ionization of residual gases in voids of window bodies. Discussion of this problem indicated general agreement with Stanford Research Institute on the order of magnitude of pressures of residual gases within the voids, and agreement that the ionization process was probably a diffusion-controlled phenomenon.

C. Dr. J. Pentacost - Melpar

Dr. Pentacost is engaged primarily in measurement of the high temperature dielectric properties of materials. His equipment and facilities are excellent, probably among the best in the country. The measurement technique used is described in a number of his reports; it consists of a platinum waveguide with the dielectric material as a termination of the guide. A well designed and regulated oven is used to maintain the dielectric at temperatures at which measurements are made. His experience in measurements has indicated that stress can play

an important part in the dielectric properties of materials. This stress may be residual or applied to the material. He is setting up to conduct experiments to verify these observations.

D. D. Churchill - Sperry Gyroscope Company

Mr. Churchill has made significant contributions to the understanding and solution of high power window problems. He feels on the basis of his experience that at present power levels the most important window problem is multipactor on the vacuum side of the window. He also believes that "O"-cut oriented sapphire is among the best of presently available window materials for power handling capability. At his present levels of power he has observed no punctures of the sapphire window materials. In addition to sapphire, beryllia is also being looked at as a high power window material. In his experience the major problem with sapphire is that of making the seal to the waveguide. He is not certain about the upper limit of performance of presently available materials, but believes that there is a need for more fundamental material studies if higher power windows are to be achieved.

E. Professor P. J. Warter - Princeton University

Dr. Warter is in the electrical engineering department at Princeton. He is concerned with space charge effects and transport phenomena in insulating materials. At present he is preparing to publish the results of a series of studies on the current-voltage relationships in a number of materials. He indicated that space charge effects would be significant in the breakdown process.

F. Professor R. Smoluchowski - Princeton University

Dr. Smoluchowski is a prominent solid state physicist. He did not have any specific comments other than to indicate the difficulty to be expected in trying to plot the electronic structure of aluminum oxide. However, he believes that a first order approach could lead to a firmer basis for understanding its behavior.

G. Dr. A. Rose - RCA Research Laboratories - Princeton

Dr. Rose is one of the pioneers in the study of space charge effects in insulators. His work goes back as far as 1951. He feels that injection of carriers and distribution of traps in the dielectric material will be very important in the breakdown process. He suggested that considerable thought be given to this facet of the problem and that care be taken in the development of experiments to study the injection and trapping processes. He believes that experiments on breakdown should be conducted in a manner such that the influence of carrier injection is well controlled and understood.

H. Professor P. Gibbs - University of Utah

Professor Gibbs has done considerable work in the study of dislocations in aluminum oxide. He believes that defects such as dislocations can have important effects on the breakdown process in an insulator. He also suggested that one of the biggest problems in studying the behavior of the material could be the difficulty in growing single crystals of the aluminum oxide. He pointed out that in polycrystals the boundaries could be locations of concentrations of impurities, and that, therefore, in determining the effects of impurities it would be necessary to use a single crystal material with controlled impurity content.

I. Professor G. Wannier - University of Oregon

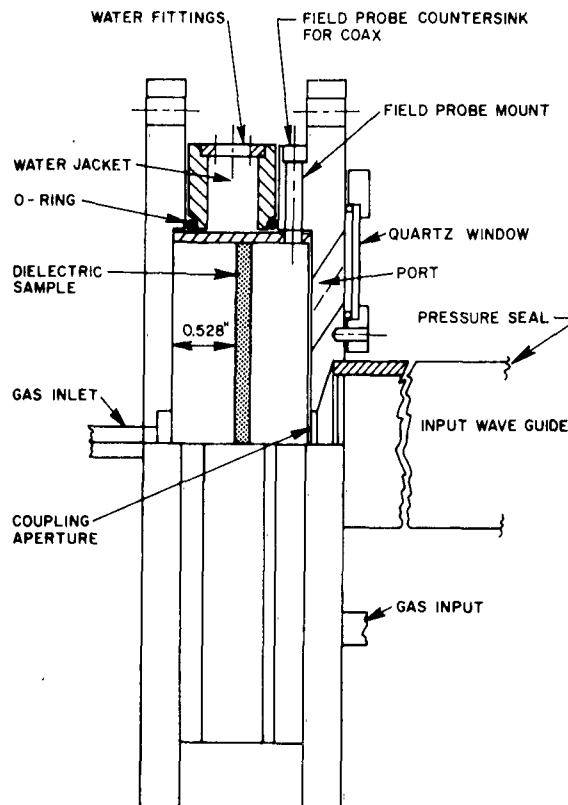
Professor Wannier believes that the use of ultrapure material for an insulator may not be too desirable. His comment is based on the concept that with impurities in a material the bottom of the conduction band is distorted in such a form that a number of small barriers are introduced. These barriers may be considered as impeding the transfer of electrons lying in low levels of the conduction band. With the use of high purity material there is a possibility that the barriers would be reduced and thereby allow a clear path for movement of electrons under an applied field.

J. Conclusions Resulting from Visits

The general concensus of the people visited was that the possibilities of impurities acting as both traps and donors or acceptors must be investigated thoroughly and carefully; this also applies to defects. Account must be taken of the anisotropy of the material and of the effect of strain on its behavior. These comments, while quite general, are the results of studies of a number of insulating and photoconductive materials. It is interesting to note, however, that to date there has been little investigation, of a fundamental nature, of aluminum oxide. This is probably because this material is considerably more difficult to study due to its structure and large band gap.

IV Ionization of Gas in Voids in Windows

A cavity had been designed for testing the window materials as described in Report No. 1. Figure 1 is a drawing of the cavity-window assembly. However, the negotiations, mentioned in the previous report, for a subcontract with a local microwave tube manufacturer to have the high power r.f. testing performed for this task, were abruptly terminated at the end of this quarter, because the Company's internal use factor for the necessary facilities had suddenly risen to the 100% level. Therefore, every effort is being made to obtain the early use of such facilities elsewhere, in order to avoid further delay in performing this task.



RA-4180-2

FIG. 1 CAVITY ASSEMBLY

V Electrical Measurements on Sapphire

A. Description of Resistivity Experiment

The atomic picture of a grain boundary is not known to any detailed extent, since in most cases the boundary is extremely complicated. In the case of aluminum oxide (polycrystalline) the boundary is formed at an elevated temperature with a sintering compound. Such a boundary introduces perturbations in the lattice potential. These perturbations will modify the wave function of the conduction electrons and macroscopically change the conductivity of the material. Figure 2 represents an energy level diagram for an ideal polycrystalline material. This model excludes impurities which may act as donors, acceptors, or traps. The bottom of the conduction band is not a straight line because the individual crystals are randomly oriented. The random orientation with respect to the direction makes the location of the fermi level, within a given crystal, a function of x . When these crystals are in contact with each other, the fermi level must be at the same level throughout the bulk material. This results in a stepping of the conduction band energy levels as a function of x , as shown in Figure 2.

Figure 3 is a model of a grain boundary which might exist in a real polycrystalline material such as aluminum oxide because the boundary is formed with an additive material. Since the impurity content is high the step height (or junction) may be quite large compared with the ideal model in Figure 2. The points P_1 and/or P_2 may be above the bottom of the Al_2O_3 conduction band or below the top of the Al_2O_3 valence band, depending upon the impurities in the additive, the impurities in the crystals of Al_2O_3 , and the additive itself. In the former case a

barrier to electron flow would exist, if point P_1 is several KT^* above the top of the Al_2O_3 conduction band.

Measurements made on aluminum oxide and sapphire^{11,12} involve both impurity and grain boundary effects; thus, little is known about their individual effects on transport processes. If more were known about grain boundaries it might be possible to modify the conduction and breakdown parameters of aluminum oxide, for example, lower leakage current and higher breakdown fields.

The approach taken here is to form a single, large area, grain boundary between two oriented sapphire crystals. By this method comparison measurements may be made between sapphire samples without a grain boundary and sapphire samples with a grain boundary. Measurements on conductivity versus temperature, current versus voltage, and voltage breakdown will be made on the comparison samples. From these data it will be possible to improve our knowledge of the physical picture of grain boundaries in aluminum oxide.

B. Sample Preparation

A sapphire boule was obtained from Linde Crystal Products. The boule's c-axis orientation was determined by X-ray diffraction techniques. Samples were cut in disc form with the c-axis parallel to the surface of the disc. The thicknesses of the samples were about 0.040 in. and their diameters were about 0.500 in. Four discs were selected and polished flat. One disc is to be measured in its present crystalline state. Two other discs were sintered together with a compound consisting of about equal parts calcium carbonate and silicon dioxide (Figure 4). The calcium

¹ $KT = .025$ electron volts at room temperature

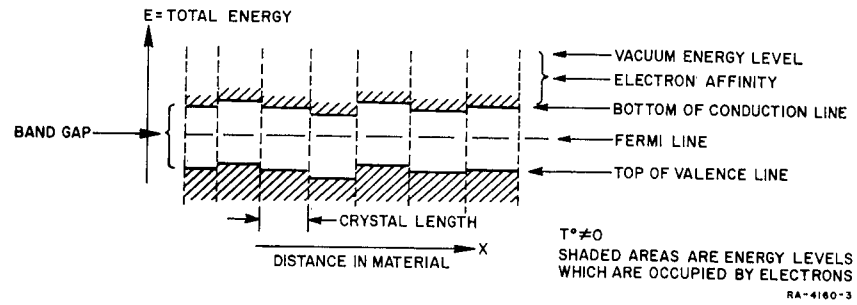


FIG. 2 ENERGY BAND MODEL FOR IDEAL POLYCRYSTALLINE MATERIAL

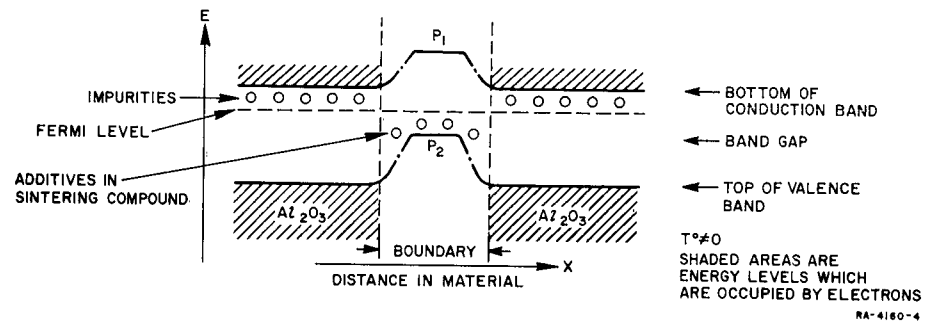


FIG. 3 MODEL OF GRAIN BOUNDARY

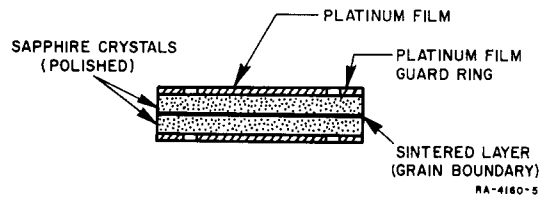


FIG. 4 SINTERED DISCS (Cross-section)

carbonate-silicon dioxide powder was ground to produce very small particles and mixed with distilled water to form a paste. This compound represents a typical sintering compound used by industrial firms to produce polycrystalline alumina. The stacked crystals were fired in air, along with the fourth piece, at 1750°C for 3 hr. The two pieces of sapphire were firmly bonded together after this firing. The fourth piece was included in the firing so it would have the same temperature history as the stacked crystals. The stacked crystals with the grain boundary represent a typical grain boundary such as is present in polycrystalline alumina.

C. Experimental Apparatus

The apparatus to be used for measurements involving elevated temperatures is shown in Figure 5. Figure 6 is a schematic of the electrical circuit. The oven is capable of reaching 1100°C as recorded with the chromel-alumel thermocouple. The quartz tubes reduce leakage paths to ground and provide mechanical supports for the platinum leads within the furnace. Contact between the platinum leads and the sample is made by mechanical pressure, exerted through the quartz tubes, on the platinum wires. The lead to the electrometer is carefully isolated from the surrounding circuitry. The capacitor (1 microfarad, 100 volts) bypasses alternating currents to ground. The maximum background noise current is 2×10^{-13} amp, which is at least an order of magnitude less than the sapphire currents to be measured.

1. Sapphire Electrodes

The electrodes on the sapphire are in the form of a central disc with a surrounding ring. The ring is a guard ring which eliminates measurements of leakage currents on the sapphire surface.

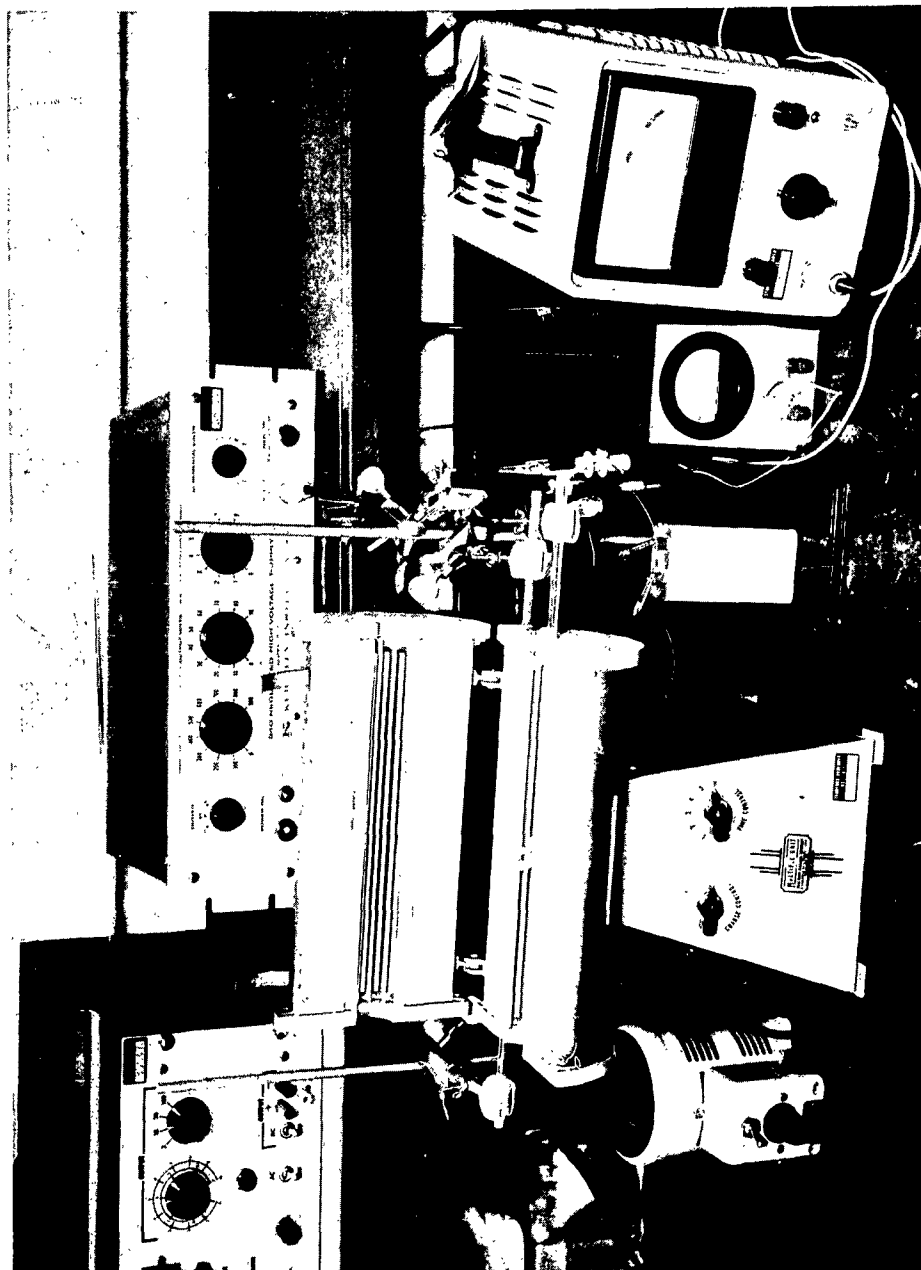
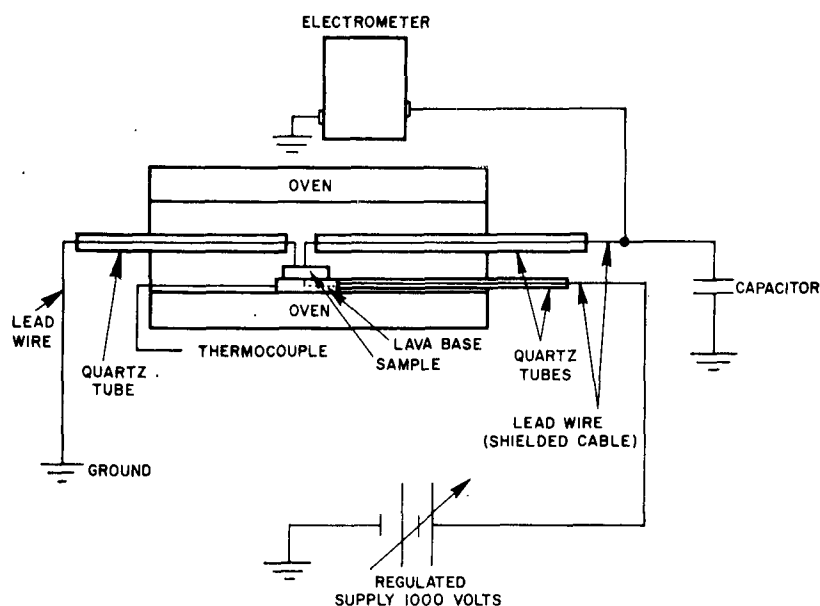


FIG. 5 EXPERIMENTAL APPARATUS



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FIG. 6 EXPERIMENTAL APPARATUS (Schematic Diagram)

The electrodes on the sapphire samples are platinum and gold. Platinum and gold paint is painted on the sapphire samples after they have been washed and rinsed in trichlorethylene and alcohol. The sample is then fired at 800°C in air for 1/2 hour, thereby removing the binder and producing an adherent metallic film. It is essential that the wet film be placed in the oven at room temperature or flaking of the film will occur. In order to form a guard ring the film is scribed in a circle with a diamond pencil, resulting in a central circular disc surrounded by a ring. The films resist attack by aqua regia and are highly adherent. Figure 7 shows the temperature limit of both gold and platinum films fired in air as measured in our laboratory.

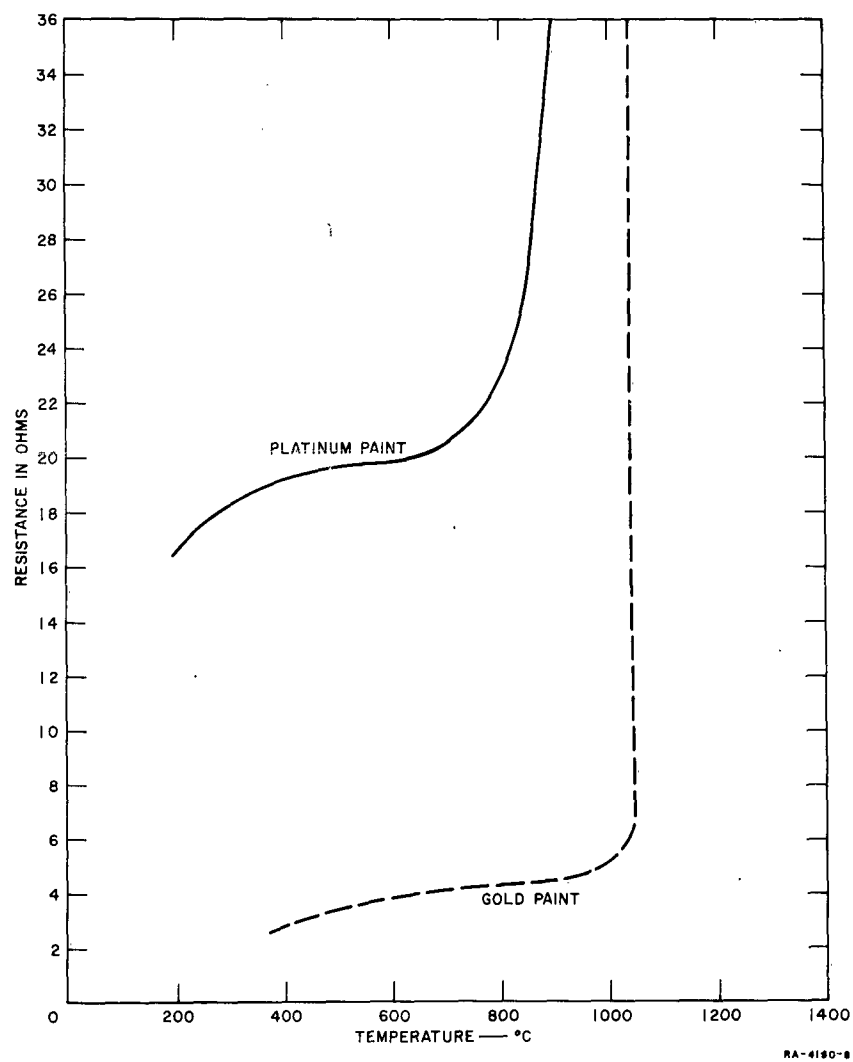


FIG. 7 RESISTANCE vs. TEMPERATURE

2. Lead Wires

Platinum wires, 0.005 in. and 0.010 in. in diameter, were attached to the electrodes on the sapphire samples by brazing techniques. The platinum-coated sapphire sample, platinum lead wire, and gold braze material were cleaned in trichlorethylene and rinsed in methanol. The sample was placed in the air furnace with the gold braze material between the platinum film and the platinum wire. The temperature of the oven was briefly raised to 1080°C. The strength of the resulting braze was limited by the film adherence to the sapphire sample. The gold braze method is satisfactory for applications where only moderate mechanical stresses are involved.

3. Subsequent Work

Measurements will begin immediately, using the aforementioned equipment and samples. The initial measurements will be of current versus temperature and current versus voltage on the three sapphire samples.

D. Spin Resonance Experiments

An additional set of experiments concerned with identification of vacancies in single crystal sapphire has started. Disks of "O"-cut sapphire about one-quarter in. in diameter and about 0.020 in. thick have been prepared with leads soldered to each face. The disks will be suspended in a cavity of a spin resonance test facility and exposed to either electron injection or u.v. excitation. The free electrons generated by these methods will be trapped in the vacancies. By determining the width of the absorption lines, the number of vacancies in the specimen can be determined. First tests of the untreated specimens indicate low background noise, or signal, so signals resulting from electrons filling the vacancies should be observable.

VI Experiments on Growth of Aluminum Oxide

A. Vacuum Equipment

1. High Vacuum Equipment

The high vacuum system, designed to operate at a pressure of about 5×10^{-7} Torr, has been installed and checked out. This system was fabricated by Vactite to meet specifications set forth by Stanford Research Institute. The system, complete with an adapter ring and assorted feed-throughs, has been cycled a number of times and has operated satisfactorily on all operations. This constitutes the outer portion of a double-wall, or two-chamber, system having essentially the same basic design as the system used by Shoulders.¹

2. Construction of Ultrahigh Vacuum Chamber

The ultrahigh vacuum chamber and the associated components are being fabricated; however, problems in heat dissipation of the base plate and in fabricating techniques concerned with welding operations have caused delays in the construction. The components are tested in existing systems as they are completed, to facilitate the final assembly of this unit when all parts are ready. The unique features of this system are the method of chemical pass-through from high vacuum to ultrahigh vacuum and the methods of manipulation of materials within the system. Both of these methods are described in detail in the work by Shoulders¹ and by Hansen, et al.¹³ The chemicals to be used as source materials in the film deposition are to be sealed under vacuum in quartz ampules with break-off tips. These ampules will be placed in ceramic holders and will be transported into the inner system through the chemical pass-through.

The status of the individual parts is as follows.

a. Bake-Out Furnace

The bake-out furnace with water-cooling jacket, water and electrical lead-ins, and heat shields is complete and assembled.

b. Inner System Can

The main can of the inner system is complete and awaiting associated equipment for test.

c. Inner System Base Plate

A base plate for the inner system has been made and the tests on this part are in progress.

d. Ion Pump

The main components of the ion pump have been fabricated; complete construction of all parts is awaiting some special assembly experiments.

e. Manipulators

Fabrication of the component parts of the manipulators is in progress and completion is expected soon.

f. Chemical Pass-Through

The chemical pass-through is being fabricated and will be ready for installation at the time of final assembly.

g. Electronic Components

Electronic components used in connection with the inner system are being assembled and will be ready and pretested before the time of final assembly of the inner system.

h. Substrate Heater Furnace

A substrate heater is being fabricated and will be used in the interim work as soon as assembly is completed.

3 Interim Experimental High Vacuum Equipment

The fabrication of the ultrahigh vacuum equipment is taking longer than was originally expected, as was mentioned above. In the interim, experiments are being conducted in other available high vacuum equipment. The prototype equipment setup shown in Figure 8 was used for checking heating requirements for source and substrate heaters. Figure 9 shows the equipment used in the feasibility studies, the chemistry of which will be described in a later section of this report. The substrate heaters in these experiments were flat wire filaments and the substrate was in intimate contact with the filament. This made it necessary for these experiments to be performed with a nonconducting material as the substrate. An additional discussion of this work is described in the section on Experimental Deposition Work.

B. Deposition Techniques

There are several known methods for preparation of thin films of aluminum oxide. Some of these have been studied at Stanford Research Institute by other groups for specific purposes. These methods are:

- (1) reactive deposition of Al_2O_3 in vacuum, using AlCl_3 and NH_4NO_3
- (2) reactive deposition of Al_2O_3 in vacuum, using AlCl_3 and H_2O
- (3) reactive deposition of Al_2O_3 at atmospheric and low pressure, using AlCl_3 , H_2 and CO_2
- (4) oxidation of bulk aluminum at slight positive pressure, at atmospheric pressure, and at low pressure, using gaseous oxygen and aluminum.

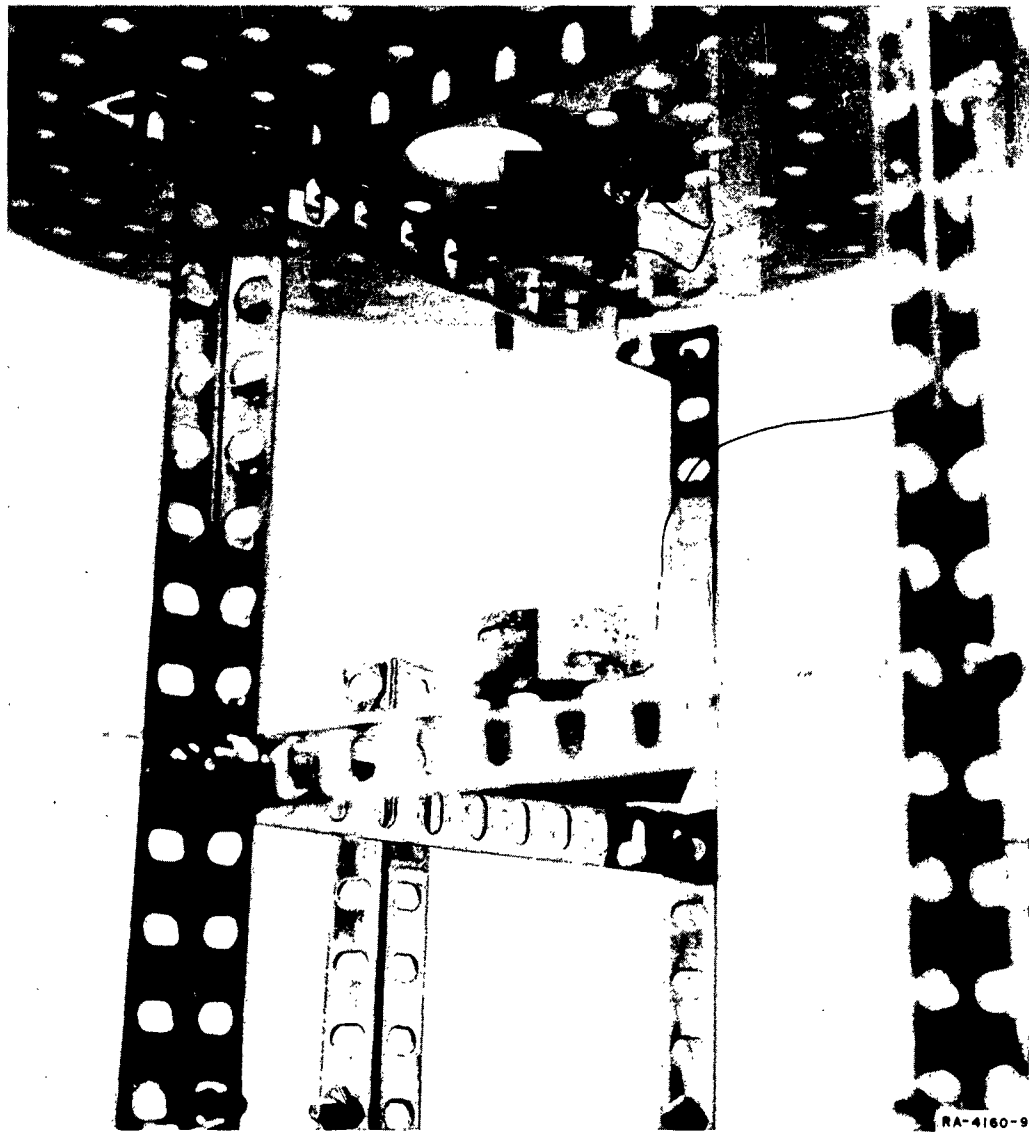


FIG. 8 PROTOTYPE REACTIVE DEPOSITION APPARATUS

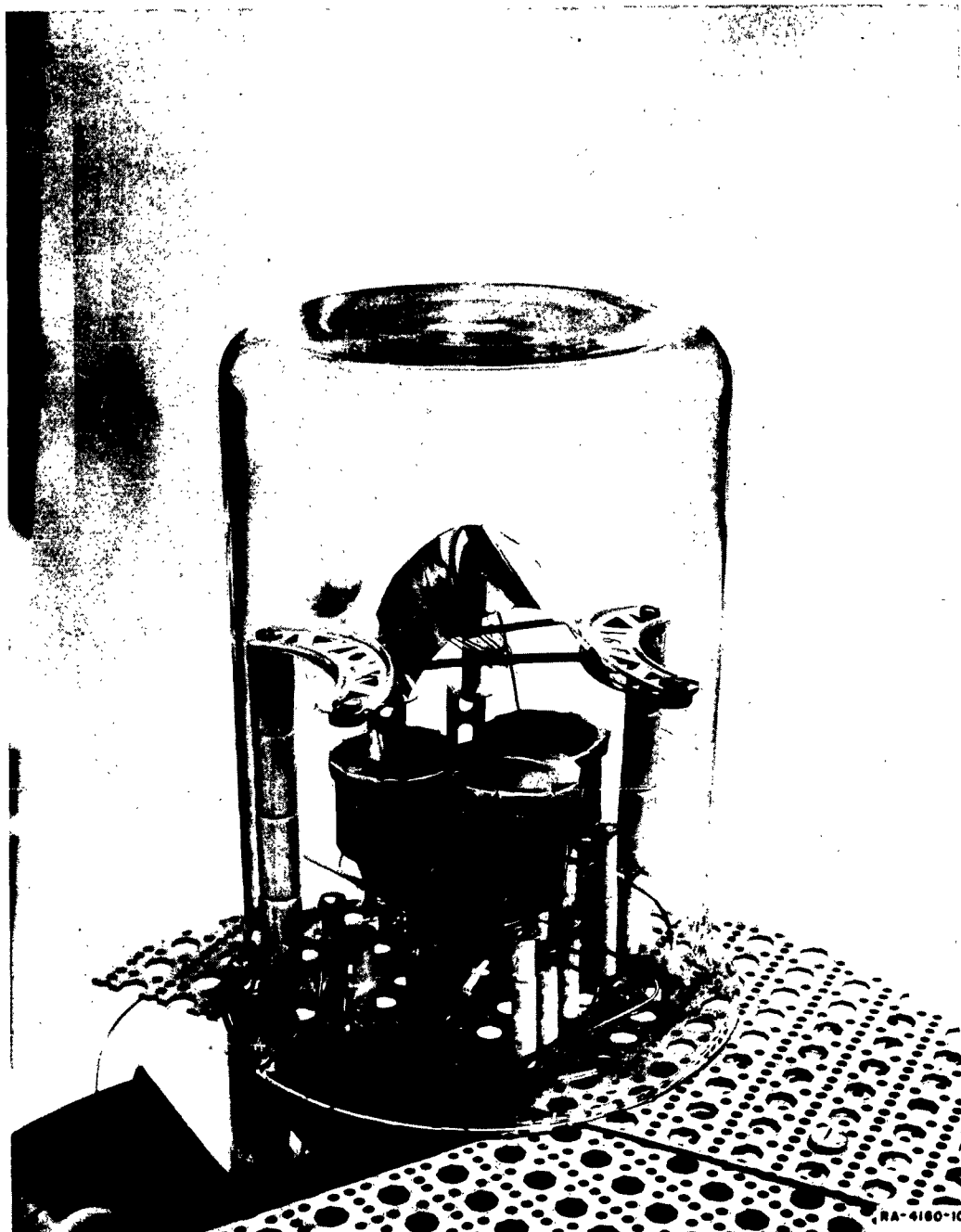


FIG. 9 REACTIVE DEPOSITION APPARATUS

Several other methods may also be found in the literature; however, most of these involve solution reactions. The chemicals used in a given reaction must be of such a physical nature as to permit sealing in quartz ampules under vacuum for transport into the ultrahigh vacuum chamber.

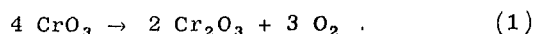
The primary concern in selecting a reaction to be used in this project was the potential improvement in the level of purity of the resultant film. An attempt to increase this purity level of the films requires that one carefully investigate the possible reactants for purification schemes and also the nature of the products obtained in addition to Al_2O_3 .

Method 4 above was given serious consideration because it appeared that this would be the simplest and most direct means of preparing Al_2O_3 with the least amount of impurity in the source material. It was recognized that an oxide film prepared in this manner could lack stoichiometry unless some special precautions could be developed. The chief reason for continued consideration of the method was the possibility that aluminum in the 8 nines purity can be obtained and that systems exist for producing oxygen of comparable purity. It is our judgement that it should be possible with this method to produce Al_2O_3 films of purity comparable to the source aluminum.

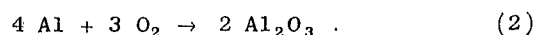
1. The Environment Yielding Oxygen

One method of obtaining oxygen is from a metal oxide as a result of the metal changing to a lower oxidation state. The requirement for the metal oxide is that it thermally dissociate at a reasonably low temperature and yield, in addition to oxygen, a product which is thermally stable at the working temperature.

Chromium trioxide was the metal oxide chosen because it appeared to fill the requirements. The literature shows the decomposition reaction to be:



This reaction takes place at 471°K.^{14,15,16} The oxidation reaction for aluminum is:



On the basis of using a material which would meet criteria previously mentioned, this reaction would appear to be one well worth consideration. The actual use of CrO₃ experimentally presents some difficulties. The material is very hygroscopic and handling is extremely difficult. It is entirely possible that one could utilize a drying scheme which would make the use of CrO₃ more readily adaptable to high vacuum techniques.

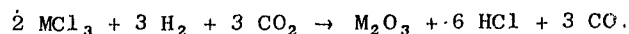
2. The Oxygen Environment

Another method utilizing oxidation of aluminum to form a film of Al₂O₃ involves the use of oxygen from a gas source. This method would involve the use of a leak-control device. Such devices are commercially available for use in high vacuum systems and consideration is being given to possible modification or redesign to permit the use of this type of device in ultrahigh vacuum. It is recognized that direct application of commercial units is not possible at this time.

3. Volatile Metal Halide-Hydrogen-Carbon Dioxide Reaction

The reaction between a volatile metal halide, hydrogen, and carbon dioxide will form the metal oxide at a heated surface.^{17,18}

This reaction is written in its general form as:



Powell, Campbell, and Gonser, in their text, state that the reaction may be performed using CO_2 alone with the metal halide, but that when this was done the reaction rate was very low. The authors suggest that the reason for the low rate may be the formation of phosgene which could allow the reverse reaction to become important. The reverse reaction is favored by low temperature conditions; however, at the high temperatures to be used in this reaction, the rate of the reverse reaction will be negligible.

This reaction can be carried out with any metal halide which can be volatilized below 500°C . The essential reaction involved is hydrolysis of the volatile metal halide at the hot substrate surface by the water vapor produced as a result of the water-gas reaction. This reaction has been used to produce films up to 0.004 in. thick; however, the adhesion of these thick films is very poor. Thinner films of high quality have been reported and it appears that this method might afford one of the better approaches to the preparation of metal oxide films.

This technique has been used to prepare SiO_2 and ZrO_2 as well as Al_2O_3 . The volatilization of aluminum chloride takes place at between 130 and 160°C . The substrate temperature required is in the range of 800 to 1000°C . The published data indicate that the reaction proceeds at a reasonable rate.

From the standpoint of adapting such a reaction to the system being used, the requirement is for materials which will yield H_2 and CO_2 or produce water vapor. The former may be accomplished by obtaining the H_2 from $TiH_2 \cdot xH_2$. Titanium hydride in its formation saturates with hydrogen. Upon heating, $TiH_2 \cdot xH_2$ loses hydrogen rather easily. Approximately 80% of the hydrogen is lost at $400^\circ C$, and at $800^\circ C$ to $1000^\circ C$ the reaction is essentially complete, although the actual decomposition of the hydride is slow.¹⁹ The CO_2 required for the water-gas reaction may be obtained by decomposition of a metal carbonate such as magnesium carbonate. Magnesium carbonate can be obtained in a variety of forms, with and without water and with water and the hydroxide. All of these forms will decompose at about $350^\circ C$ to produce MgO and CO_2 ; however, the two forms containing water will lose it at about $100^\circ C$.¹⁴ It can be seen that any of these three forms is readily usable for the required reaction.

4. Reactive Deposition with NH_4NO_3

The reaction between $AlCl_3$ and NH_4NO_3 is being used by another group at Stanford Research Institute. The experimental technique to be followed in the application of this method will be essentially the same as that being used by them.¹³

5. Reactive Deposition with H_2O

No extensive experimental consideration has been given to this reaction; however, it will be studied to ascertain whether or not it can be adapted.

C. Experimental Deposition Work

Experimental work to determine the laboratory feasibility of possible methods has begun. Studies of the chemistry and techniques of preparing the materials for use have been carried out. Initial experiments on formation of films have been started.

1. Decomposition of Chromium Trioxide

A small crucible heater has been made and tested for use in the decomposition of CrO_3 . Observation of the decomposition reaction indicates that it goes well at about 200°C , or 471°K , as the literature indicates. A sample of CrO_3 was heated to 200°C slowly; the time to reach 200°C from room temperature was 45 minutes. The 0.4702-g sample was held at temperature for approximately 9 minutes. The pressure of the system decreased approximately 2 orders of magnitude. The weight of the residue was 0.2465 g, which would indicate that approximately 30% of the original sample might be water.

Attempts to dry high-grade, wet, "Chemically Pure" Reagent CrO_3 have so far met with little success. Additional experiments are planned to attempt to dry the material in vacuum.

2. Studies of Water-Gas Reaction

Initial experiments using AlCl_3 , $\text{TiH}_2 \cdot x\text{H}_2$, and $\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot \text{H}_2\text{O}$ have been performed on a feasibility basis only; the indications are that some degree of success was attained. Three experiments were run all in the following way.

- a. Three crucibles were carefully cleaned and dried in a vacuum oven.

- b. A sample of the chemicals listed above was placed separately in each of the three crucibles and each crucible was placed on its heater in the vacuum system.
- c. A cleaned and dried piece of sapphire substrate was placed in the substrate heater.
- d. The system was evacuated to a pressure of 1.4×10^{-6} Torr.
- e. The substrate was heated to $1000^{\circ}\text{C} \pm 50^{\circ}\text{C}$ and held at that temperature. The substrate was allowed to outgas and the system returned to the previous pressure.
- f. With the substrate at temperature, the three source heaters were slowly brought to predetermined temperature conditions for each reactant material.
- g. The reaction was allowed to proceed for 30 minutes, after which time the source heaters were turned off.
- h. The substrate was held at temperature for 5 additional minutes before being allowed to cool to room temperature.
- i. The system was raised to atmospheric pressure and the substrate removed.

The substrate used for these experiments was an alumina disc. This material was used because the design of the substrate heater required a nonconductive material. Preliminary optical examination show evidence of film formation; however, the nature of the film could not be determined.

More refined experimental techniques are being prepared to allow for better control of the heating of both source materials and substrate. These include better heat shielding surrounding all components and especially separating the sources and the substrate. In the initial experiments, it was noted that the source materials were heated by the excessive radiation from the substrate heater. A substrate heater which will allow for a more uniform distribution of heat across the substrate is being installed.

The equipment necessary to use the mass spectrometer to attempt to detect impurities in the source materials is being constructed. This consists of a source heater, appropriate shielding, and a thermocouple to follow the temperature of the source material. Weight loss measurements will also be performed on the source materials.

D. Mass Spectrometer

The quadrupole mass spectrometer components are complete. The leads are presently being hydrogen-brazed to the proper electrodes and assembly will begin during the first week of January.

CONCLUSIONS

There is a possibility of identifying the different types of breakdown in dielectrics if the breakdown conditions can be correlated with the condition of the dielectric at the time of test. That is, there must be a knowledge of impurity content, trap distribution, and defect status.

In performing tests to identify breakdown mechanisms, the effect of electron injection by metallic contacts to the dielectric must be accounted for. In studying avalanche, collective, or field emission effects, nonmetallic contacts are preferable.

Platinum and gold coatings may be used as contacts for making electrical measurements on aluminum oxide in air up to temperatures in the range of 1000°C .

The reaction between a volatile metal halide, hydrogen, and carbon dioxide will form aluminum oxide on a heated substrate.


PROGRAM FOR NEXT INTERVAL

The following activities are planned for the next interval:

1. The theoretical study of the electronic structure of aluminum oxide as influenced by its crystal structure will continue.
2. The construction of the ultrahigh vacuum system will be continued and testing of component parts will be performed as parts are available.
3. Studies and experiments on growth of aluminum oxide films will continue.
4. Measurements of properties of aluminum oxide single crystals and compacts will continue; among these tests will be studies of space charge in aluminum oxide.
5. It is hoped that a subcontract for conducting the high r.f. power tests of window ceramics will be executed as early as possible, and that the measurement phase of this task on the effects of voids can be started.

KEY TECHNICAL PERSONNEL

L. Feinstein, Project Leader, 248 hours.
J. Bordeaux, Physical Chemist, 484 hours.
D. Peters, Research Engineer, 442.5 hours.


Lester Feinstein, Manager
Electronic Materials Section

LF:tf

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Initial studies of measurement of resistance of sapphire vs. temperature have been begun.

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